Failure Analysis and Recovery of a 50mm Highly Elastic Intermetallic NiTi Ball Bearing for an ISS Application

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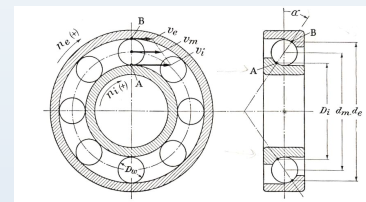
Bearing Material: State-of-Art (SOA)
(Current suite of candidates is severely limited)

- **Four general types of bearing materials:**
  - Steels (Corrosion resistant steels, martensitic, austenitic)
  - Ceramics (Si_3N_4 balls + steel races, a.k.a., hybrid bearings)
  - Superalloys (e.g., jet turbine blade alloys)
  - Non-ferrous alloys (bronze, nylon etc.)



- **Each of these has inherent shortcomings:**
  - Hard steels are prone to rusting (even “stainless steels” like 440C)
  - Superalloys and austenitic stainless steels (304ss) are soft.
  - Ceramics have thermal expansion mismatch and dent steel races
  - Non-Ferrous materials are weak and lack temperature capabilities
- **No known bearing material blends all the desired attributes:**
  - High hardness, corrosion immunity, toughness, surface finish, electrical conductivity, non-magnetic, manufacturability, etc.

Technical Properties Comparison: 60NiTi

Property	60NiTi	440C	Si_3N_4	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 HRC	58 to 62 HRC	1300 to 1500 Hv	60 to 65 HRC
Thermal conductivity W/m-°K	~9 to 14	24	33	~36
Thermal expansion	$\sim 11.2 \times 10^{-6}$/°C	10×10^{-6}/°C	2.6×10^{-6}/°C	$\sim 11 \times 10^{-6}$/°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent (Aqueous and acidic)	Marginal	Excellent	Poor
Tensile/(Flexural strength)	~1000(1500) MPa	1900 MPa	(600 to 1200) MPa	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness	~20 MPa/√m	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Maximum use temp	~400 °C	~400 °C	~1100 °C	~400 °C
Electrical resistivity	$\sim 1.04 \times 10^{-6}$ Ω-m	$\sim 0.60 \times 10^{-6}$ Ω-m	Insulator	$\sim 0.18 \times 10^{-6}$ Ω-m

- ***Modulus is ½ that of steel, yet hardness is comparable.***
- ***Ultra-high static load capacity.***
- ***Tensile strength akin to ceramics.***
- ***NiTi alloys are brittle but do not rust.***

AMS History: NiTi Milestones

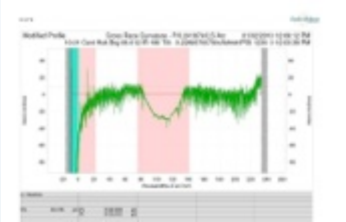
- 40th AMS (2010): Poster introducing 60NiTi
  - Successful production of ½ inch diameter grade 10 balls
  - Cast 60NiTi plates used for other materials characterization
  - Favorable hardness and tribological behavior
- 41st AMS (2012): Feasibility established
  - Paper presenting design of a 50mm NiTi bearing for ISS Urine Processor.
  - Corrosion immunity and high load tolerance (flat plates) observed.
- 42nd AMS (2014): Exceptional properties revealed
  - Static load (dent) capability shown to exceed that of bearing steel.
  - Trade study done for launch vibe sensitive applications.
- 43rd AMS (2016): Setback: painful lessons learned
  - Infant mortality bearing failure in ground test in late 2014.

BACKGROUND: 60NiTi Target Application-ISS Urine Processor Distillation Assembly Bearings

***Problem**: Bearings in the ISS urine processor utilize soft superalloy races and hard ceramic balls to withstand the corrosive environment but are prone to wear and damage from assembly and shock loads.*

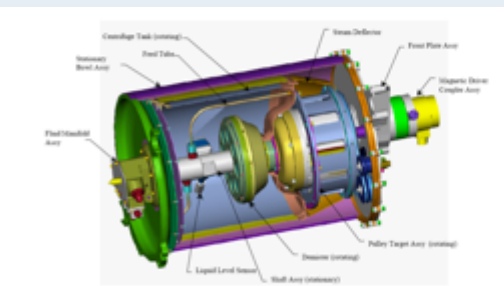
***Approach**: Engineer corrosion proof, shock proof 60NiTi bearings that can be a drop-in replacement.*

Superalloy Centrifuge bearing races

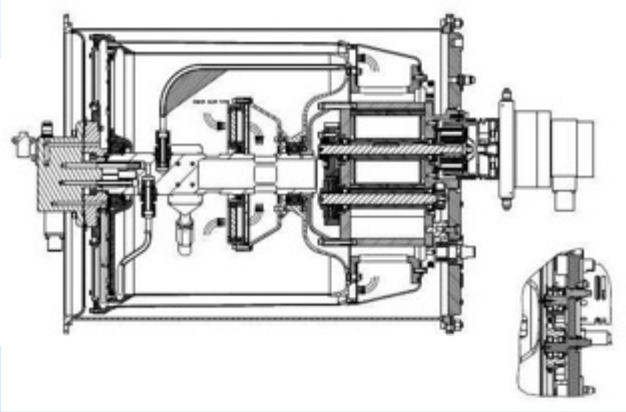


Unit #2 raceway wear

Distillation Assembly



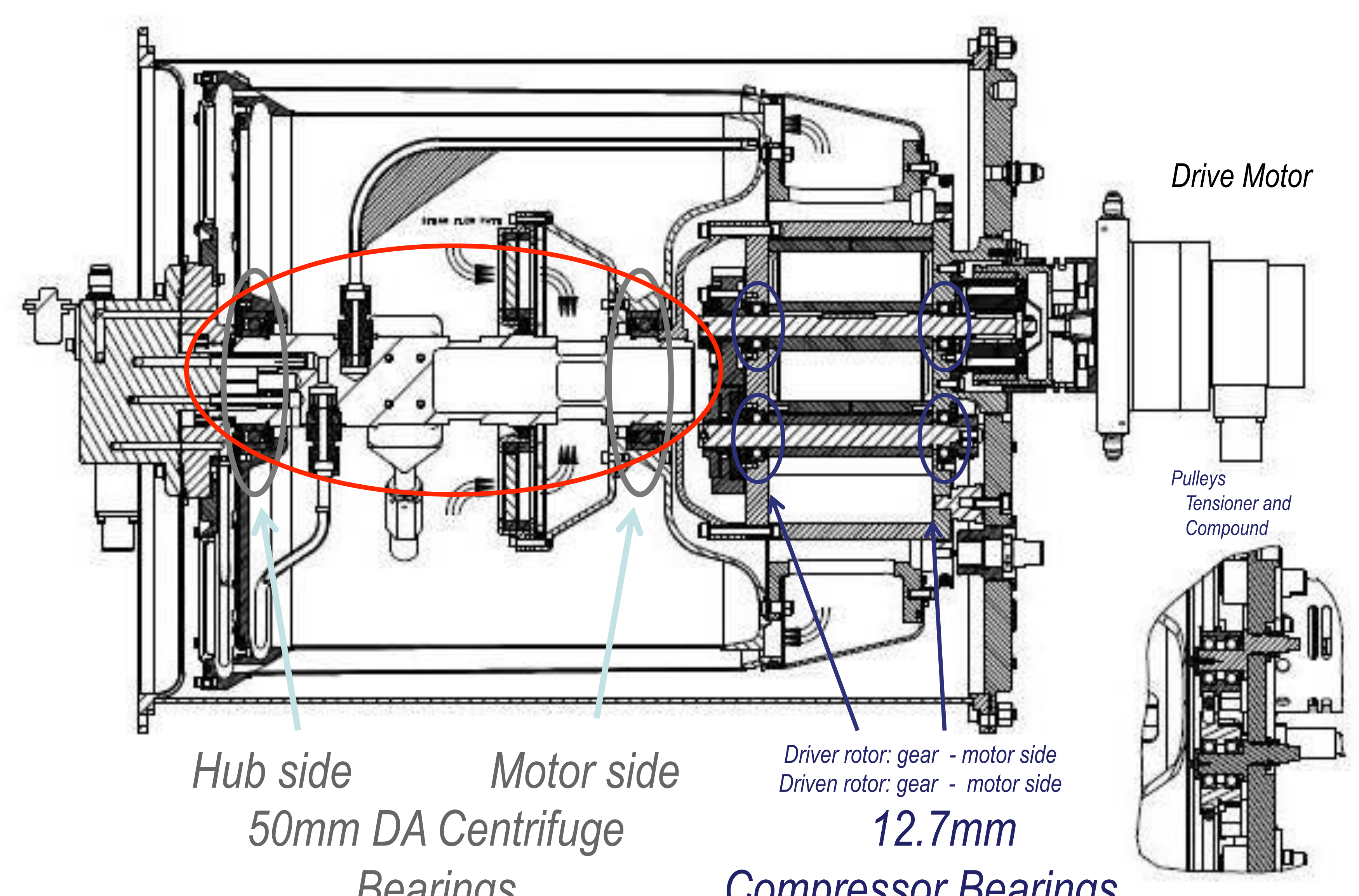
DA Schematic



***Project history**:*

- ***NESC funded team produced prototype centrifuge bearings in 2012.***
- ***Follow-on ISS effort produced batch of flight quality bearings for ground tests in a functioning DA at MSFC.***
- ***Unexpected bearing failure in late 2014 led to this failure investigation.***

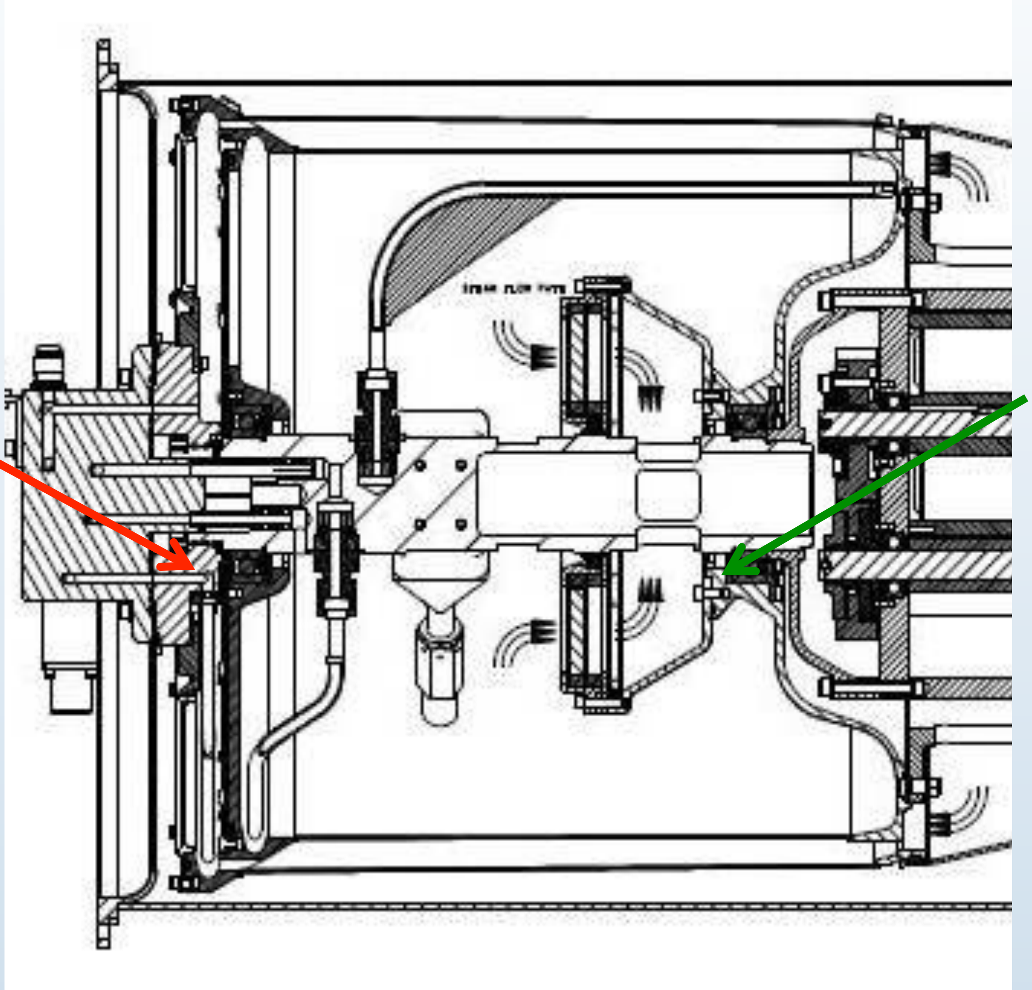
ISS Urine Processor: 60NiTi Bearing Locations



Centrifuge Bearing: 50mm bore 60NiTi Hybrid

Bearing Test: 2014 at MSFC in DA Ground Test Unit

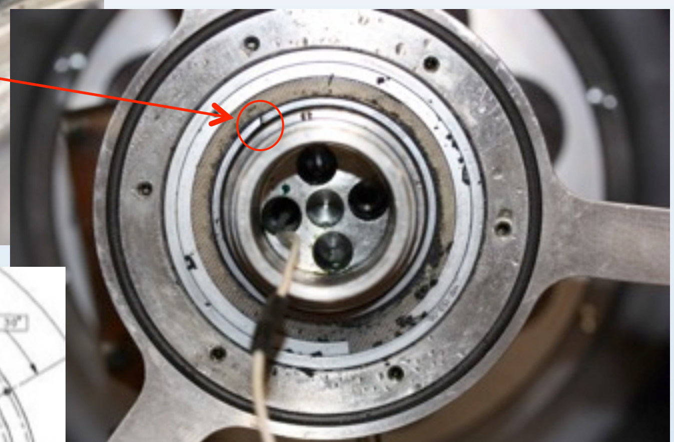
Rear hub bearing is pressed into this bore. It failed from an inner race crack after 200+hours of operation. Wear debris noted before audible bearing noise.



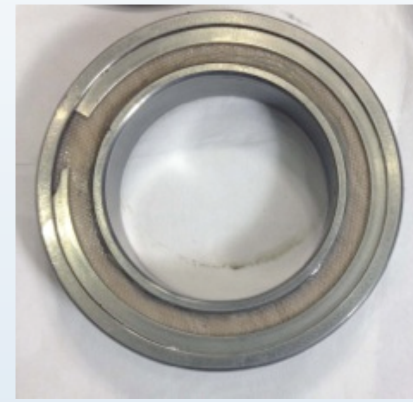
Front motor-side bearing is pressed into this bore. It did not fail at all.

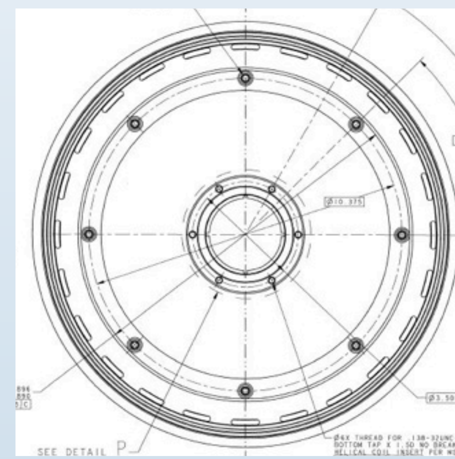
DA Post Test bearing Photos: Prior to removal

Hub Side
(Cracked inner race)



Motor-Side
(As new condition)



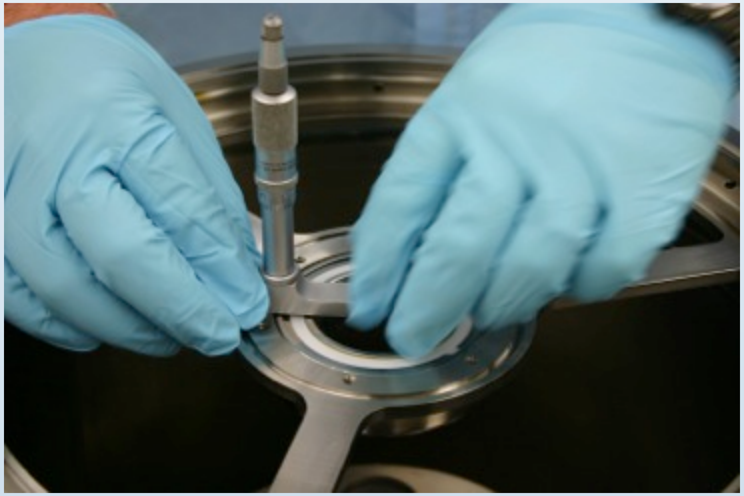


Bearing Design Fits:

- ***Outer race with 0.0006" press fit***
- ***Inner race: 0.0001 to 0.0006" clearance***
- ***Spring preload on inner race is 40 lbs***
- ***Bearing internal clearance was 0.0008" for both bearings.***

DA bearing Installation: Bearing OD Pressing


BEARINGS ARE PRESSED WITH TOOLING DESIGNED TO APPLY PRESSURE ON BOTH THE INNER AND OUTER RACES.

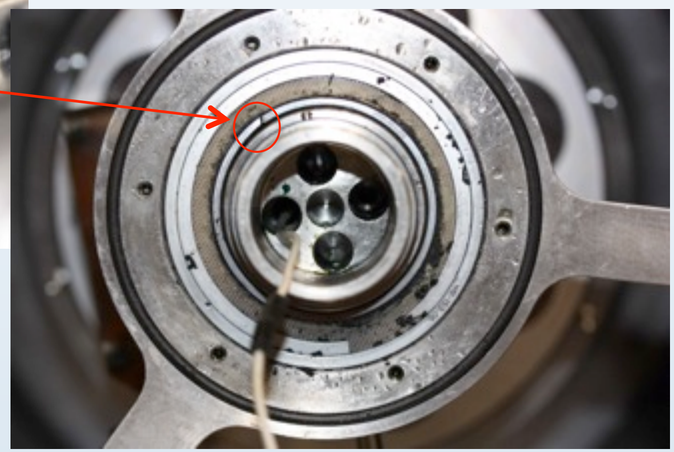



EACH BEARING IS INSPECTED TO ENSURE PROPER SEATING.

DA Post Test Measurements: Bearing Outer Race was tight

Hub Side

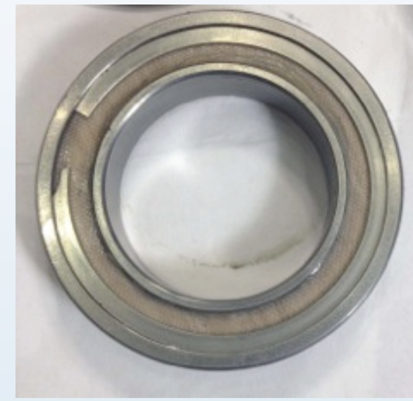
(Cracked inner race)



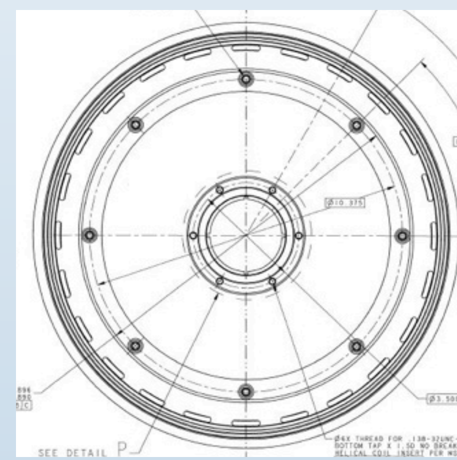
Outer Race: 0.0011" interference fit in bore.

Motor-Side

(As new condition)



Outer Race: 0.0007" interference fit in bore.

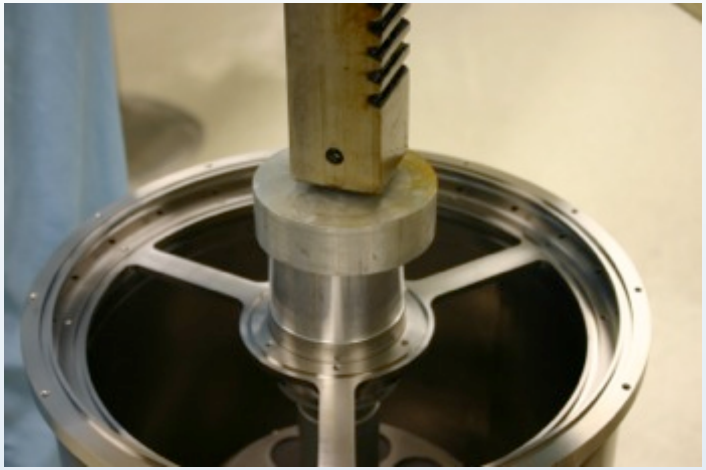


Bearing Design Fits:

- ***Outer race with 0.0006" press fit***
- ***Inner race: 0.0001 to 0.0006" clearance***
- ***Spring preload on inner race is 40 lbs***
- ***Bearing internal clearance was 0.0008" for both bearings.***

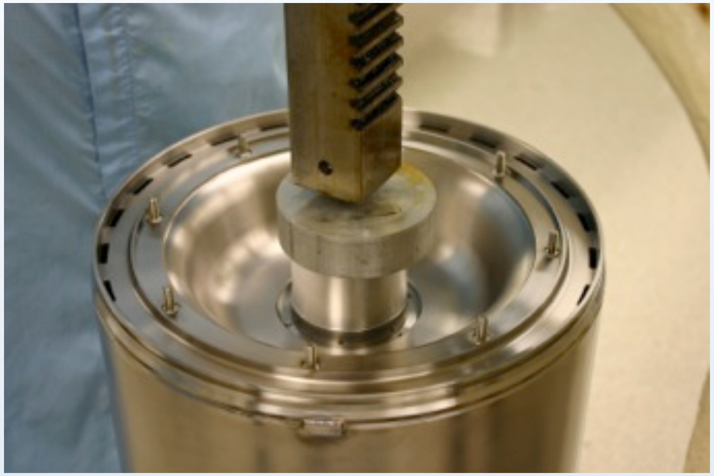
Design: Affects Axial Preload and Bearing Bore Shape

Hub Side



- Bearing bore has three attachment points (spokes) with low axial rigidity and high radial rigidity.
- Heavy interference fit of a bearing race results in tri-lobe shape of outer race.
- Low axial stiffness of structure results in some loss of spring preload and possibly dynamic motion during operation.

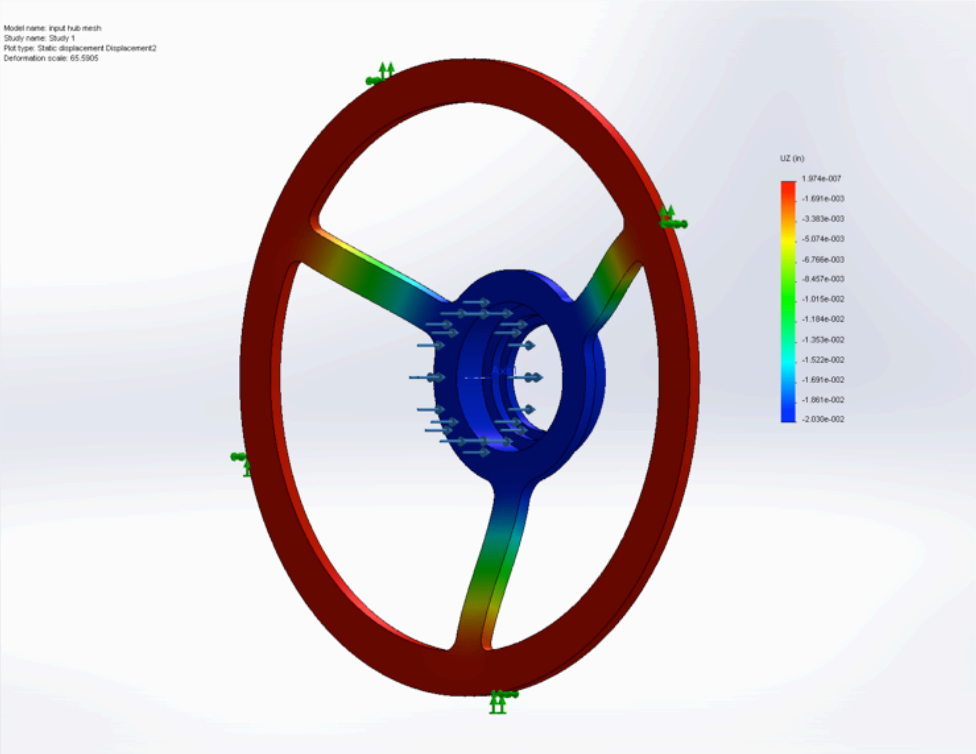
Motor Side



- Bearing bore is axis-symmetric with high axial and radial rigidity.
- Heavy interference fit of a bearing race retains round shape of outer race.
- Elastic compression of outer race will reduce internal clearance between balls and races.

Spoke Hub: Axial Deformation at 200 pound axial load

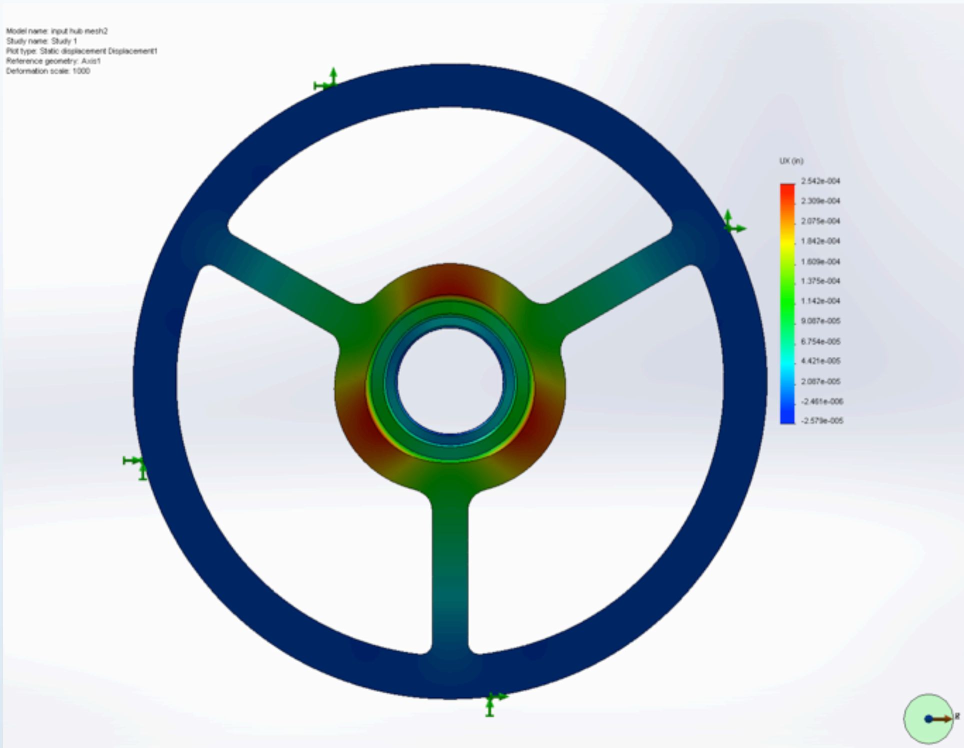
Hub Side Structure: Deformed



Axial Load Results in spoke deflection:

- ***Reduction in axial spring preload force of about 10% (35 vs. 40 lbs).***
- ***Hub bore retains original round shape.***

Spoke Hub: Radial Deformation-Interference Fit Bearing



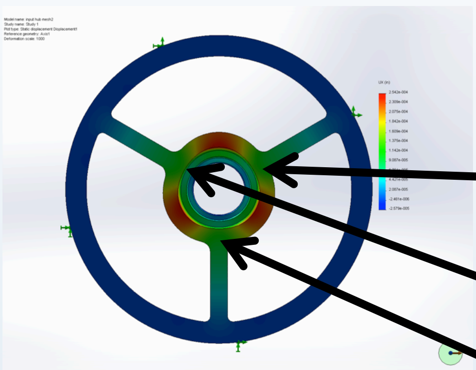
Deformation due to 0.0011” interference fit between bearing OD and hub bore.

Asymmetry (spoke design): Impact

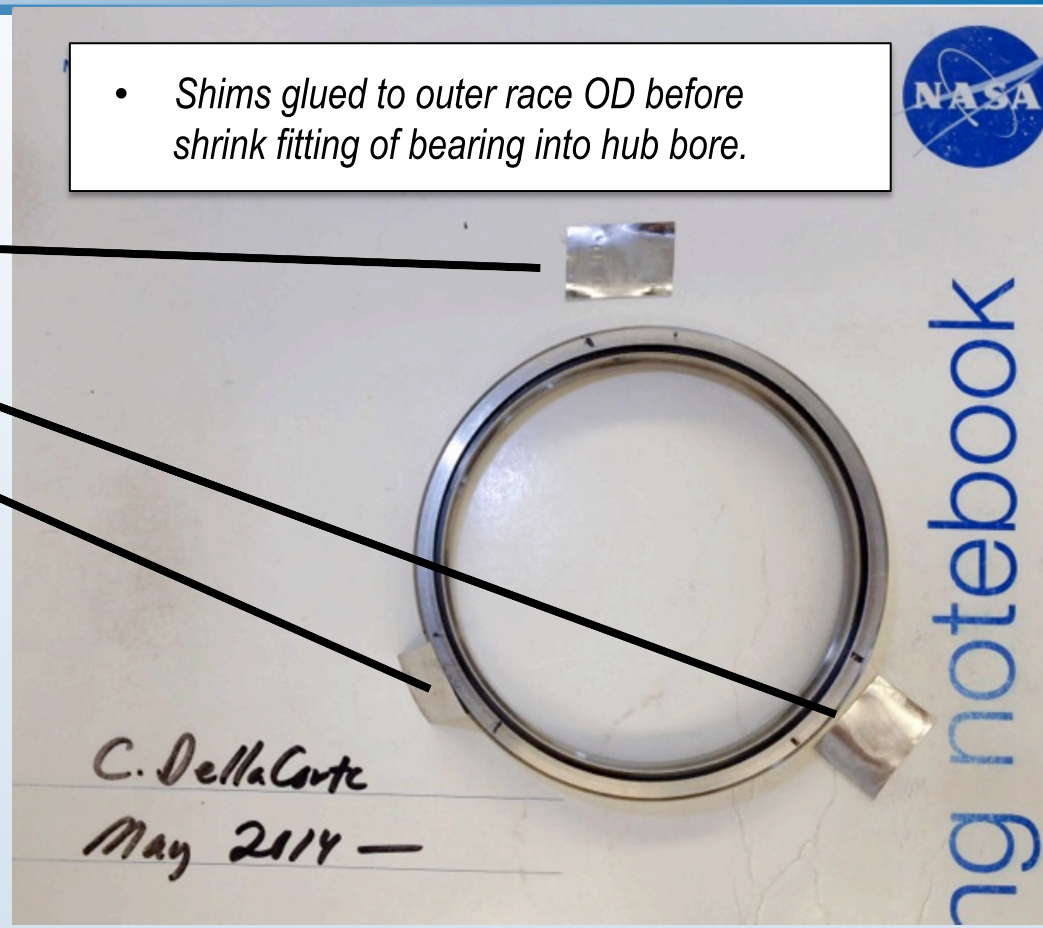
- ***Spokes present hard points that deform bearing outer race.***
- ***Heavy interference (tight) fit reduces internal clearance.***
- ***Bearing outer race is not circular in installed condition.***

Experimental Simulation: Interference Fit Bearing

Modeled fit



- *Shims glued to outer race OD before shrink fitting of bearing into hub bore.*



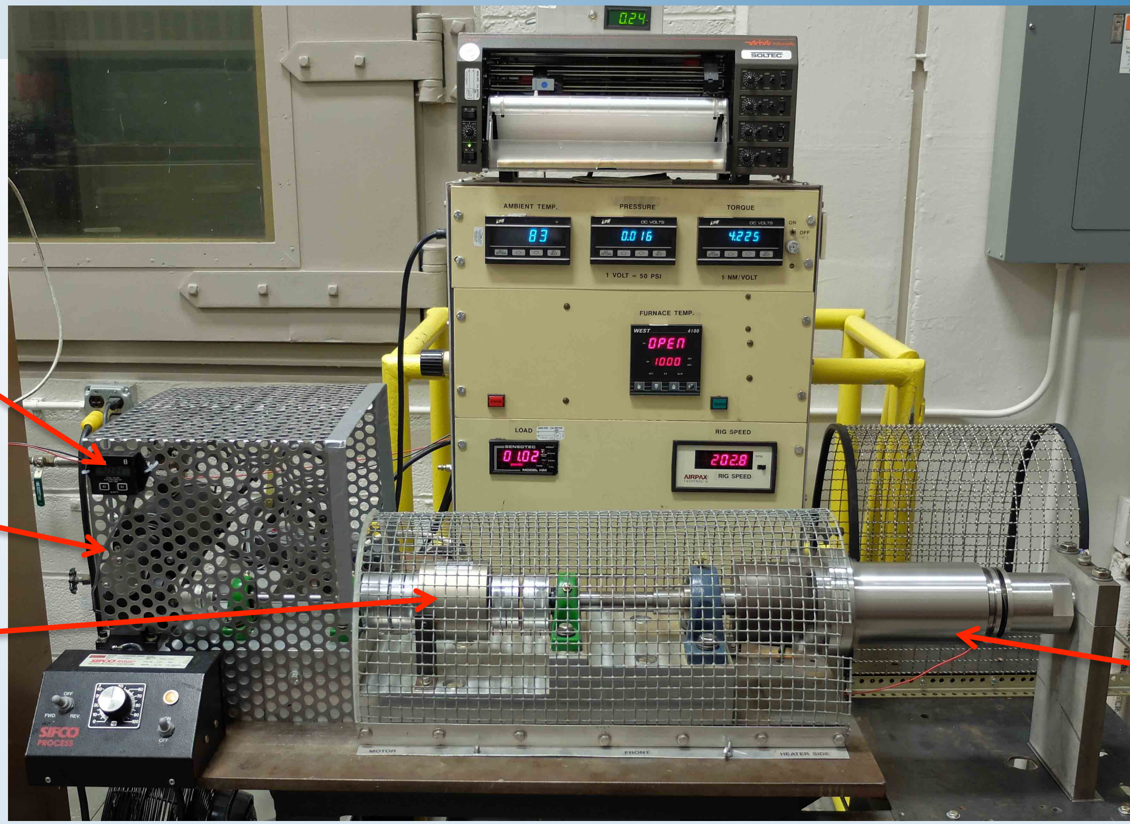
Experimentally simulated fit

- **0.001" thick shims**
- **120 degrees apart**
- **0.75" wide to ~match spokes**
- **Simulates 0.0011" interference.**
- **Motor side bearing interference fit set to 0.0003"**

Shim: Impact

- ***Shims deform bearing outer race.***
- ***Shims reduce internal bearing clearance, creating higher ball-race loads.***
- ***Not an exact reproduction of application but similar.***

Bearing Test: Shimmed Outer Race



Hour Meter

Drive Motor

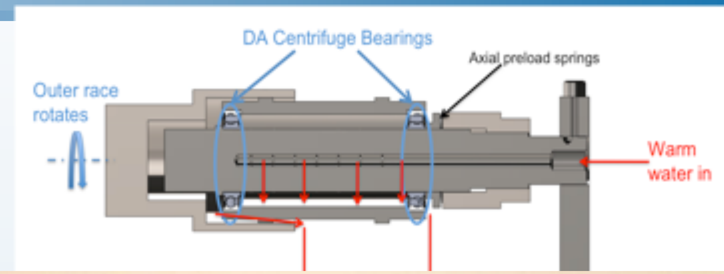
In-line Torque Sensor

Test Bearing Spindle

- *Right bearing has shimmed outer race. Left bearing properly fit.*
- *Inner races have clearance fit on stationary shaft.*
- *200 rpm, 40 pound preload.*
- *Monitor torque, inspect bearings at intervals or when audible noise observed.*
- *Recall: 2014 ground test failure occurred in ~200 hours.*

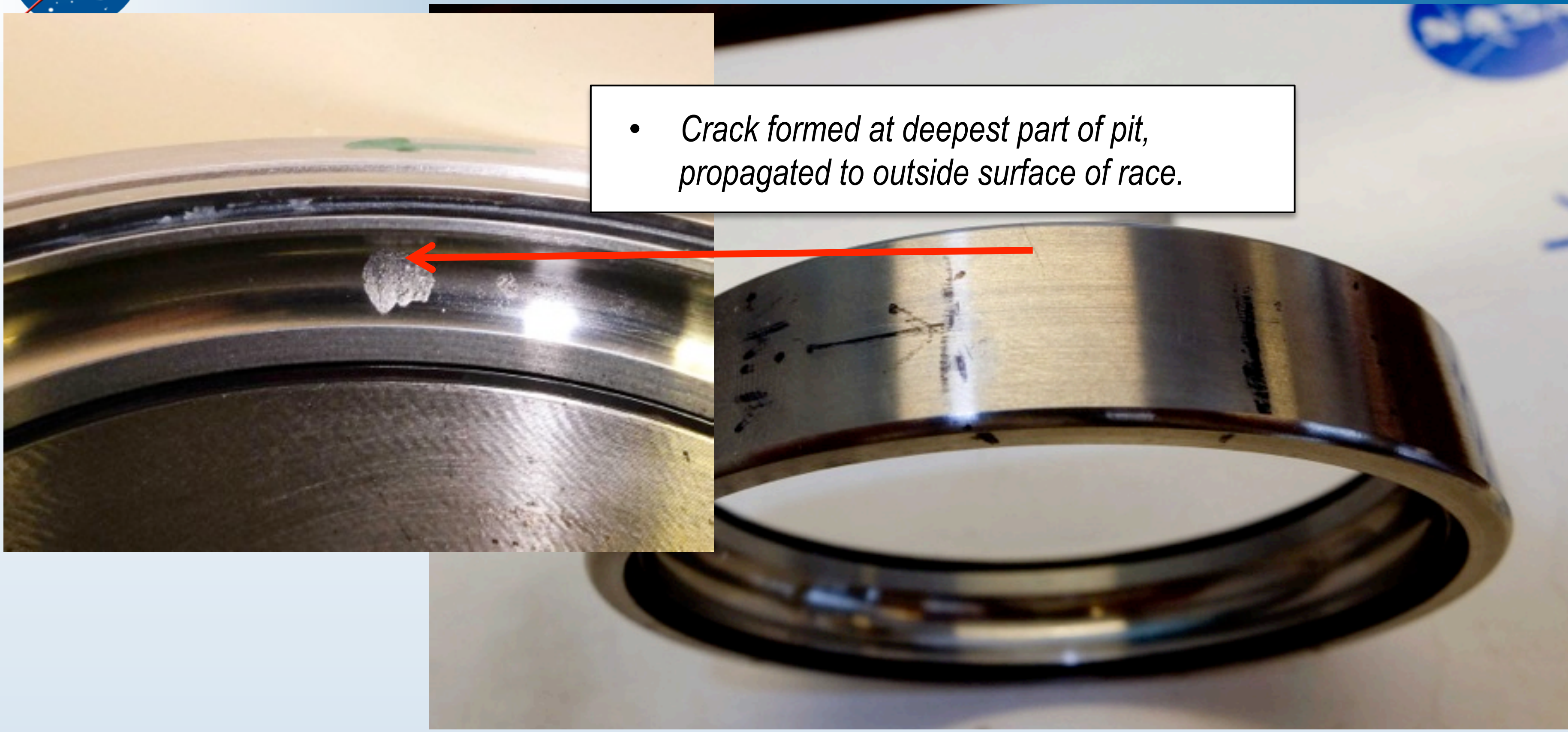
Bearing Test: Shimmed Outer Race-Results

DA Centrifuge Bearing Test Rig
Spindle Components



- *Test began normally, low torque, smooth operation.*
- *Nothing happening after 100 hours. Still quiet at 150 hours.*
- *At 157 hours, rig making noise. Shimmed bearing had uneven torque (hard spot).*
- *Inspection revealed that shimmed bearing was failed, motor side bearing was fine.*

Shimmed Bearing: Post Mortem inspection

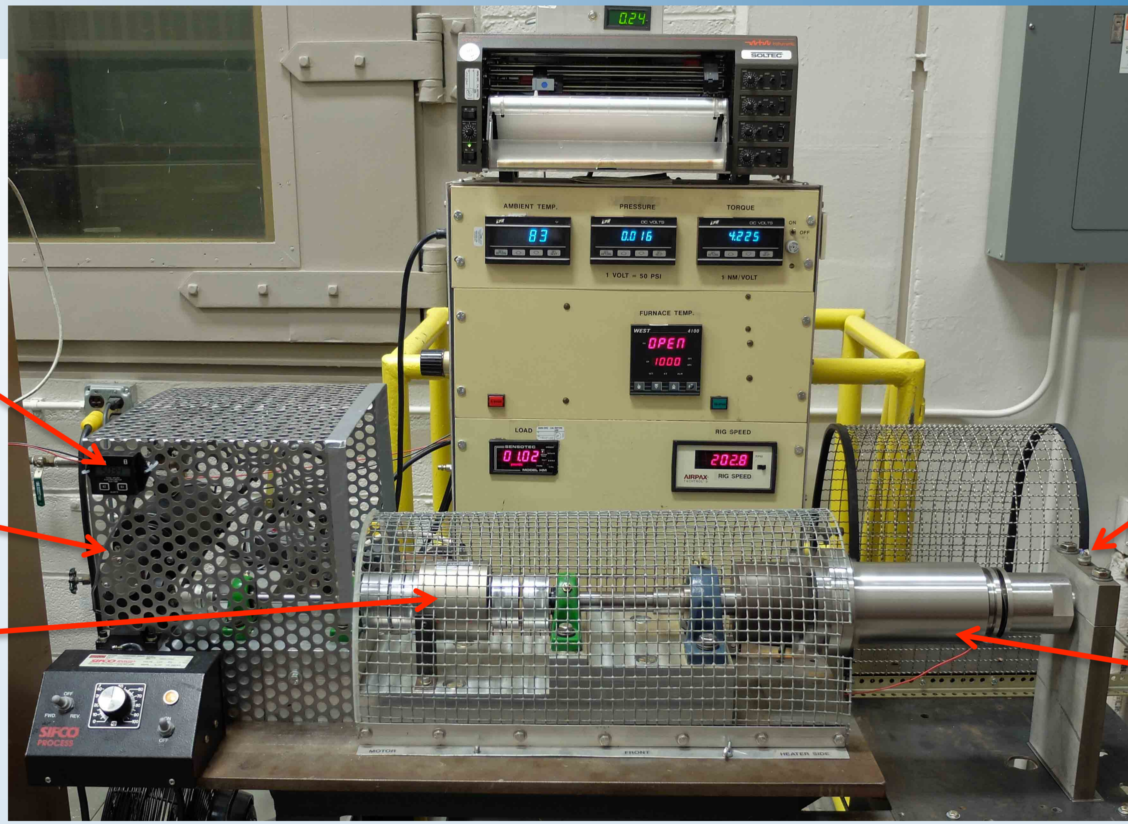


- ***Grease highly discolored and forced out of shield***
- ***Inner and outer race fatigue pits.***
- ***Deepest outer race pits progress to form race cracks.***
- ***Race cracks appear to form as secondary damage.***
- ***Test provides a possible rationale for bearing failure in DA ground unit.***

Results Summary: Root Cause Verification?

- 2014 ground test: Hub side bearing failed in 200 hours. Race surfaces were fatigued. Inner race cracked. Motor side bearing in as-new condition.
- Dimensional inspection revealed overly tight press fit.
- FEM analyses indicate distorted outer race and diminished internal clearance.
- Rapid failure mode was reproduced using shims.
- Root cause can be corroborated by a long term bearing test showing that <u>properly fit</u> bearings run without failure.

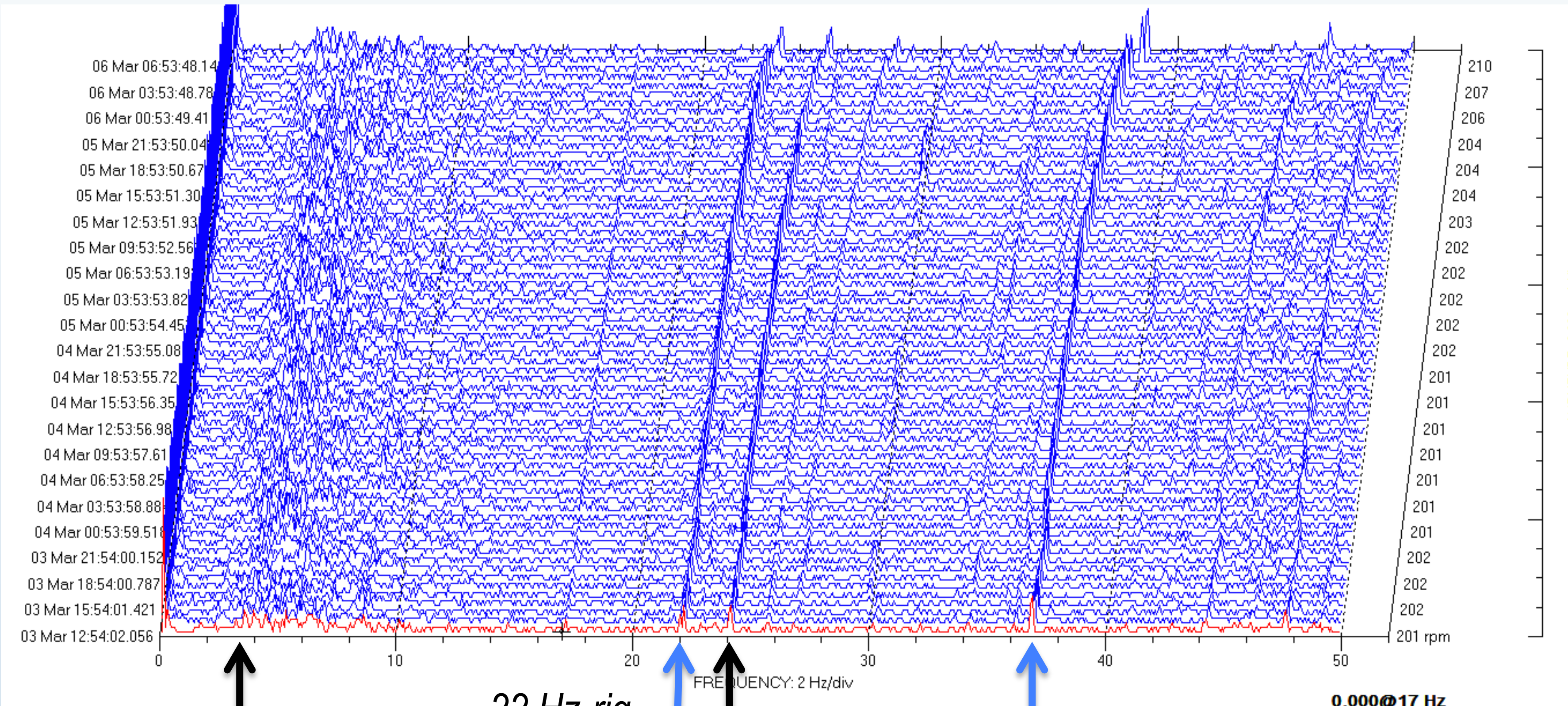
Bearing Life Test: Proper (Catalogue) Fits



- *Long-term (5000+ hour) tests begun on new flight bearings to verify life.*
- *New rig shaft and sleeve made with “to print” flight-like dimensions and DA fits.*
- Bearing bore dimensions, concentricity and square verified with CMM.
- Outer race is a line to 0.0003” interference fit. Inner race has 0.0003” clearance.
- *Accelerometer with hourly vibe spectrum data capture used for health monitoring.*
- *Interim bearing inspections at 1100, 5000 and 10,000 hours.*

Bearing Life Test: Vibration plot at 1100 hours

- *Typical vibration cascade plot for three day period shown below:*



22 Hz-rig support brg

37 Hz-rig support brg

3.2 Hz-shaft rpm

24 Hz-ball pass frequency

Bearing Life Test: Inspection at 1100 hours

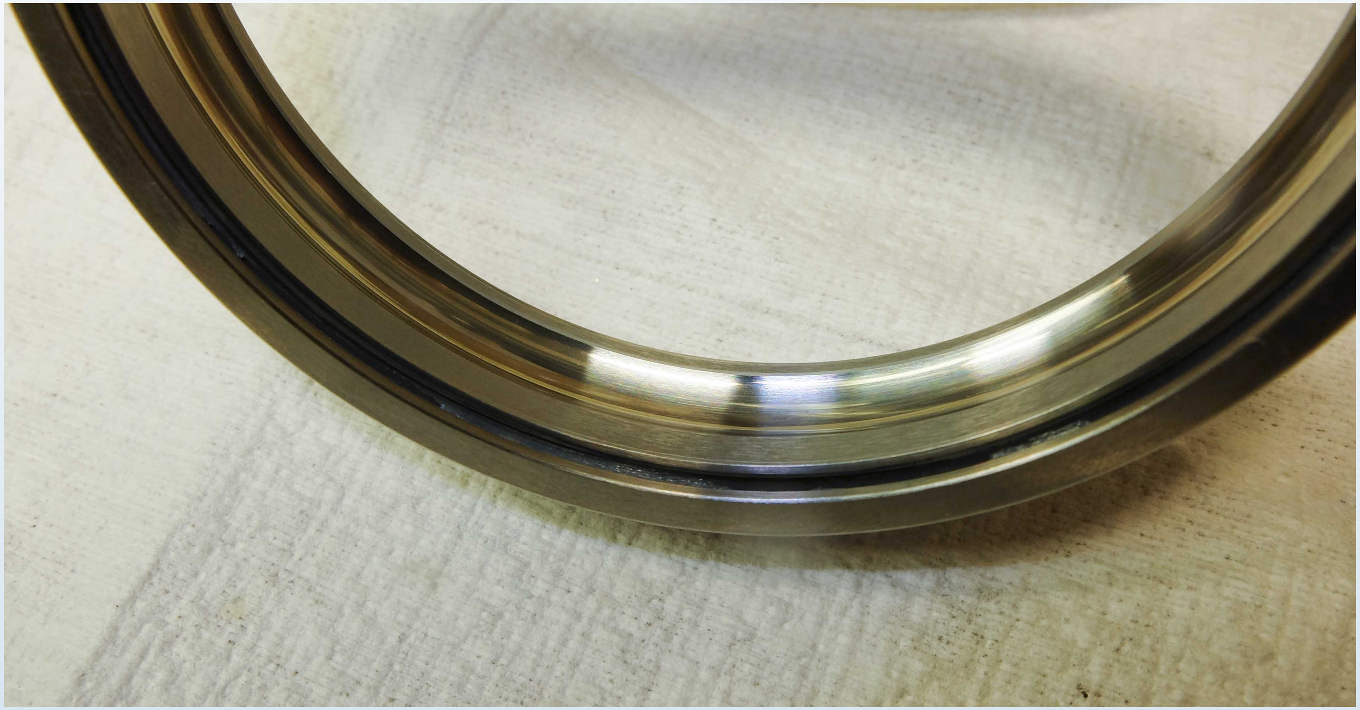
- *Lubricant grease looks new, no visible wear or damage on races.*

Bearing Life Test: Inspection at 1100 hours

- *Inner race surfaces shiny and without any apparent wear or other signs of contact damage.*

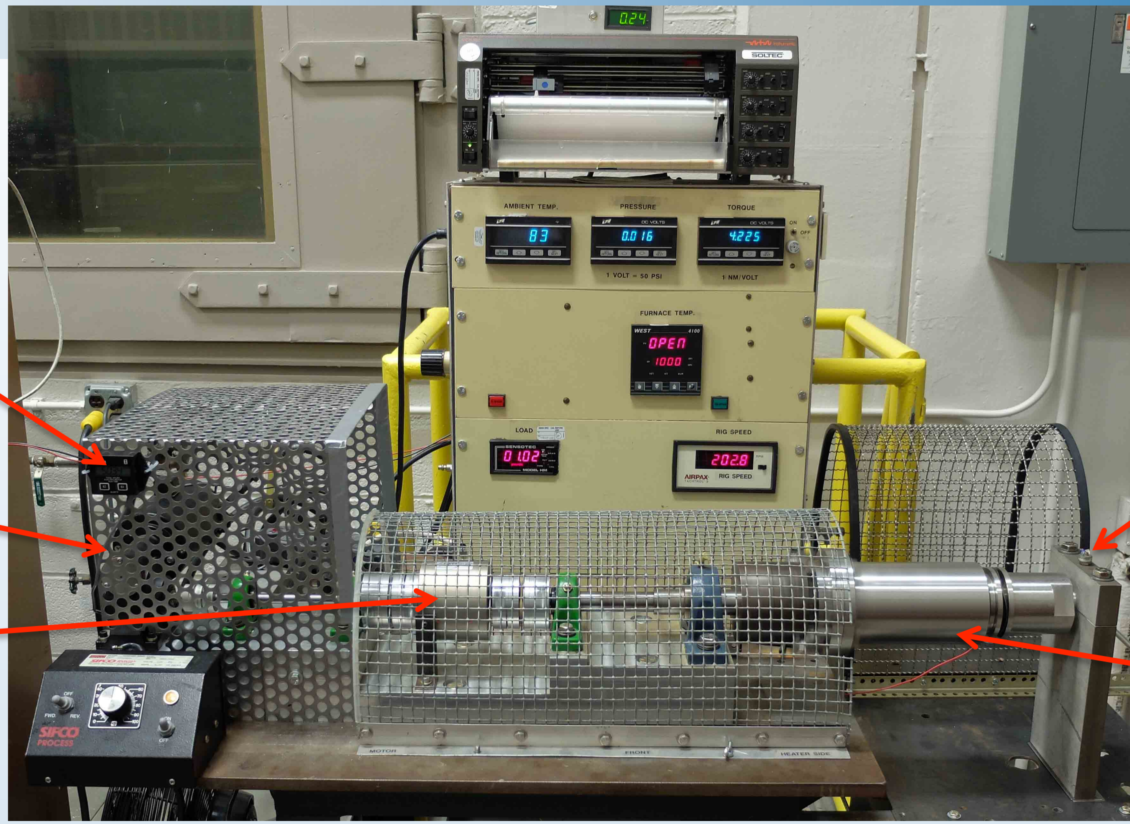
Bearing Life Test: Inspection at 1100 hours

- *Outer race looks fine too.*



- *Bearings were cleaned, visually inspected, re-greased and re-started.*
- *Health monitoring (torque and vibration) used to indicate failure.*

Bearing Life Test: continues



- *Bearings were cleaned, visually inspected, re-greased and re-started.*
- *Accelerometer with hourly vibe spectrum data capture used for health monitoring.*
- *Tests continued (24/7) until vibration changes or 5000 hours reached.*
- *5000 hour inspection revealed no changes. Tests concluded at 10,000 hour point (05/02/16).*

Failure: Root Cause & Contributing Factors

- Bearing failure in 2014 was attributed to incorrect (overly tight) fit into a non-symmetric hub.
- Brittle nature and the low elastic modulus of NiTi were contributing factors in the early failure.
- The failure mode was reproduced using shims to distort the outer race shape and minimize clearance.
- A follow on successful 10,000 hour test campaign using proper fits corroborates the design and the failure analyses.

Recovery Plan & Summary Remarks

- Careful dimensional checks of the bearings and machine interfaces (selective fitting) are essential to long-life.
- The OD of two pairs of bearings were re-ground (undersized), allowing selective fitting into existing ISS Urine Processors.

- NiTi bearing materials offer several unique attributes (high static load capability and corrosion resistance) that make them attractive candidates for space mechanisms.
- Each new application and each setback and recovery help to expand the knowledge base for these materials.
- As the technology matures, the growing knowledge-base coupled with alloy improvements will enable the mechanisms community to take advantage of NiTi's unique capabilities.

Stay Tuned!

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